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# THE STRUCTURAL FEATURES OF THE PLANETARY NEBULAE

(Annual Summary Report)

ONR Contract NonR 809-100, Project NR 046-723

by

Lawrence H. Aller  
University of Michigan  
Ann Arbor, Michigan

## 1. Introduction

The planetary nebulae are purely gaseous nebulae which derive their radiation from energy supplied by high temperature stars imbedded within them. The best known example is the celebrated Ring Nebula in Lyra, NGC 6720, although a number of the planetaries are brighter and more suited to detailed studies. Their spectra show the characteristic emission lines of hydrogen and helium and numerous so-called forbidden lines of other elements. The interpretation of these spectra has been the subject of many investigations over the past twenty-five years. The hydrogen and helium lines are produced by photo-ionization followed by recombination, whereas the forbidden lines are collisionally excited by electron impact.

Since the excitation mechanisms appear to be well understood, it was hoped that a detailed study of the emission line intensities of the forbidden lines of the light elements could lead to reliable abundance determinations. In particular, elements such as fluorine, chlorine, argon, and sulphur, which are poorly represented in stellar spectra, have lines of measurable intensity in the gaseous nebulae.

Experience showed, however, that the determination of abundances from the spectra of the gaseous nebulae was more difficult than might have been anticipated. Although the transition probabilities for the forbidden lines are accurately enough known and theoretical target areas for their collisional excitation have been computed, an interpretation of the emission line intensities in terms of abundances cannot be made without a knowledge of the structure of the nebula, i.e., the actual distribution of the radiating atoms in the envelope. The emission intensities of [NII] and [OII] cannot be compared unless the spatial distribution of the O<sup>+</sup> and N<sup>+</sup> ions is known.

## 2. Scope of the Present Investigation

The present program, a joint enterprise with Dr. Olin C. Wilson of the Mt. Wilson and Palomar Observatories, consisted of the measurement of isophotal contours of monochromatic emission lines in selected planetary nebulae. We have selected a number of medium sized and small planetary nebulae of the ring-form, binuclear, and amorphous types.

The following objects have been observed:

IC 351	NGC 6572*
NGC 1535*	NGC 6741*
J 320	NGC 6818
IC 418*	NGC 6891
NGC 2165	NGC 6886
J 900	NGC 7009*
NGC 2392*	NGC 7026
NGC 2440*	NGC 7027
IC 4593*	NGC 7662*
NGC 6210*	

Asterisks denote objects for which isophotal contours have already been measured. Most of the best plates have been reduced as of July 1, 1953.

## 3. Observational Techniques

The observations were all obtained with the coude spectrograph of the Mt. Wilson 100-inch reflector used in the slitless form. Since the coude image normally rotates in the course of an exposure, we employed the quartz optics image-rotator to keep the orientation of the image constant. Wilson replaced the slit by a tube with a hinged aluminized lid. Guiding is accomplished with the aid of a reticle in the guiding eyepiece. It is necessary to lower the lid and cut off the exposure in order to center the image. Thus, intermittent guiding is necessary and the exposure occurs while the lid is raised. The writer can attest that the guiding is difficult for an inexperienced observer. Nevertheless, Wilson has obtained some excellent spectrograms by this method. Most of the observations were made with the 32-inch camera in the spectrograph, although we observed the intense [NII] images in the bright planetary IC 418 with the 73-inch camera which gives a much larger scale.

Photometric calibration was accomplished with the aid of a wedge-slit calibration spectrograph. These calibration exposures were supplemented by plates taken with the coude spectrograph and step slits and by plates exposed behind a filter and rotating sector so adjusted as to give a known distribution of intensity across the plate. By means of these calibration devices the variation in blackening throughout an image could be converted into a variation in intensity.

#### 4. Reductions of the Observations

All the plates were reduced with the balanced-beam isophotometer invented by W. A. Hiltner and R. C. Williams.<sup>1</sup> Two analyzing beams and optical systems are used to compare the photograph under examination with a standard wedge. The operator selects a certain density on the wedge and the machine traces the contour of the same density in the photograph. The original machine has been modified and rebuilt largely by Edwin Dennison and Albert Boggess III under the supervision of Professor Mohler. The original electronic equipment and balance motors have been replaced, while photographic recording has given place to pen and ink recording. With these modifications the operator can watch the actual tracing of the contours and detect any failure that may occur in the operation of the machine.

The photometric calibration plates developed with the original nebular exposures give the relation between density and intensity for the original negative. The effect of sky-fog may be evaluated and the densities corresponding to equal steps in  $\log I_{\text{neb}}$  evaluated. The operator then selects these densities on the standard wedge and traces the corresponding contours with the machine.

Performance checks have shown that the machine faithfully repeats the contours. Different plates of the same object show the same detailed features. A further check has been made as follows. One may make successive tracings across the same monochromatic image with a conventional microphotometer, measure the abscissae of points of equal intensity and construct contours in this way. This procedure, which was first used by Berman in his pioneer work on isophotic contours in planetary nebulae<sup>2</sup> is extremely laborious and one tends to smooth out slight irregularities. Nevertheless, a comparison of contours obtained in this way for NGC 7662 with those traced by the isophotometer are in good agreement.

#### 5. Isophotic Contours of Monochromatic Images

Since each monochromatic radiation in a planetary nebula yields a separate image when the nebula is observed with the slitless spectrograph, a comparative study of the spatial distribution of incandescent hydrogen, helium, nitrogen, oxygen, neon, and other elements in various stages of ionization may be obtained. In practice, only the images of the stronger radiations are obtained; frequently there is difficulty with overlapping images. Hence, one usually analyzes only the typical radiation of a few selected ions, H, HeI, HeII, [OIII], and [NeIII], for example. In some nebulae [NeV] is also observed so that ions covering a large range in excitation are provided. The high excitation ions are usually (but not always) confined to the inner strata, the low excitation emissions often extend to much greater distances from the central star.

By way of illustration let us discuss the results obtained for NGC 7009, a double-ring structure of moderate complexity. The nebula is slightly elliptical and the weaker contours are confused with the spectrum of the central star (especially in the  $\lambda 4686$  image of HeII). The inner ring is broken and the intensity falls off gradually in the outer ring which is more nearly circular. The [OIII] and [NeIII] images are very much alike. The hydrogen image shows a greater concentration of brightness at the opposite ends of the minor axis of the bright ring. The high excitation  $\lambda 4686$  HeII radiation is confined to the inner ring and is strongest at the ends of the minor axis of the bright ring. The distribution in the inner zone more closely resembles that of hydrogen than that of the forbidden lines.

The nebulae so far studied range in complexity from nearly spherically symmetrical ring structure to intricate objects so complex as to defy interpretation in terms of any straightforward model. NGC 6572 is an example of a relatively symmetrical structure although the bright inner ring is surrounded by an amorphous mass. NGC 6210 is a nebula of the so-called "amorphous" type. The brightest portion is not at the center of the image, nor does it coincide with the position of the central star. Objects such as IC 4593 and NGC 6741 appear to have two centers of highest surface brightness. The former is a very low excitation nebula - the latter a very high excitation nebula. In NGC 2440 there are two masses of very high surface brightness which give the nebula the appearance of a nebulous double star. Two weaker "condensations" of about the same size are indicated by our isophotes. The ring structures show a great variety of form. The best examples so far reduced are NGC 1535, IC 418, NGC 7009, and NGC 7662. Attempts have been made to analyze the structure of IC 418 from conventional tracing made directly across the image. The most detailed contours have been drawn for NGC 7662 where our data are supplemented by velocity observations secured with O. C. Wilson's multislit.

NGC 2392 is the most complex object we have studied. The H, HeII, and [OIII] images are similar indicating that the high excitation radiation is not confined to the inner "ring". Although photographs with small telescopes have led observers to assign NGC 2392 to the double-ring class, the complexity of the contours and of the internal motions show that it cannot be interpreted as a single ring.

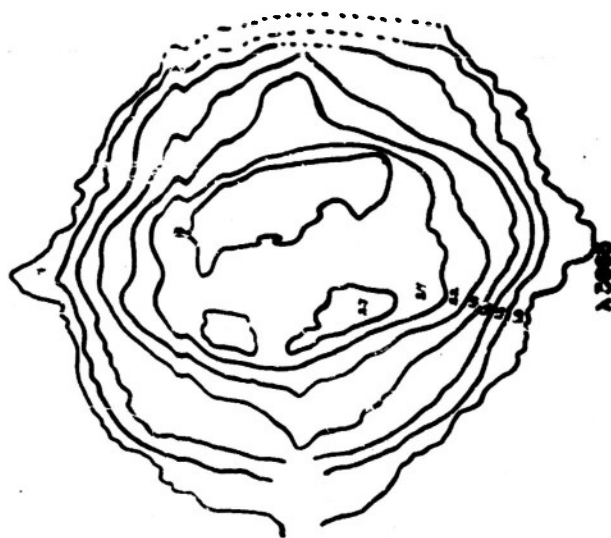
In some instances the three-dimensional structure of the nebula may be guessed from the isophotic contours supplemented by observations made with Wilson's multislit. In this device the single slit is replaced by a series of parallel slits which are close to one another. Each monochromatic image yields a series of parallel slit images broken, distorted or split by internal motions in the nebula. The relative brightness of the near and far sides of the expanding shell may be estimated from the two components of the spectral lines. Such studies are being carried out for NGC 7662. For many other objects the concept of a simple expanding shell does not appear to be adequate.

The present account is in the nature of a progress report concerning work done up to July 1, 1953. As soon as the investigation is completed we hope to prepare a full discussion for publication in the *Astrophysical Journal*.<sup>5</sup>

Thanks are due to Professor Mohler and Edwin Dennison who made many improvements in the isophotometer and particularly to Mrs. Nancy Boggess who has made all of the tracings.

#### References

1. Publ. Univ. of Mich. Obs. 8, 45, 1940.
2. Bull. Lick Obs. 15, 86, 1930.
3. See, for example, the account given in L. Goldberg and L. H. Aller "Atoms, Stars, and Nebulae", Harvard Univ. Press 1943, p. 173.
4. A. B. Wyse, Ap. J. 95, 356, 1942.
5. A report of results secured up to December 1952 was given in "Application for Renewal of Contract Non R 809(00), Proj. NR 046 723", which was submitted to the ONR office and favorably received.



10"

NGC 7009

